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Thin disk of co-rotating dwarfs: A fingerprint of dissipative (mirror) dark matter?

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ABSTRACT

Recent observations indicate that about half of the dwarf satellite galaxies around M31 orbit in a thin plane approximately aligned with the Milky Way. It has been argued that this observation along with several other features can be explained if these dwarf satellite galaxies originated as tidal dwarf galaxies formed during an ancient merger event. However if dark matter is collisionless then tidal dwarf galaxies should be free of dark matter – a condition that is difficult to reconcile with observations indicating that dwarf satellite galaxies are dark matter dominated. We argue that dissipative dark matter candidates, such as mirror dark matter, offer a simple solution to this puzzle.

Recently the discovery of a vast, thin plane of co-rotating dwarf galaxies orbiting the Andromeda galaxy [1] has been reported. It was found that about half of the satellites of the Andromeda M31 galaxy belong to a vast extremely thin planar structure (about 400 kpc in diameter but only about 14 kpc in thickness). The structure is co-planar with the Milky Way to M31 position vector and is almost perfectly aligned with the pole of the Milky Way's disk. Of the 15 satellites in this thin plane, 13 of these were found to be co-rotating sharing the same direction of angular momentum. A similar planar structure but not so extremely thin and not so numerous (nine satellites with one counter-orbiting) was found earlier among Milky Way's dwarf satellites [2]. Such vast coherent planar structures constitutes an interesting puzzle from the point of view of the standard Concordance Cosmology [3].

Such structures can be understood if the satellite galaxies originated as tidal dwarf galaxies. It was suggested by Zwicky long ago that new dwarf galaxies can be formed as a result of violent disruptions of galaxies during close encounters [4]. When two galaxies interact, tidal forces rip out matter from the galactic disks thus providing enough intergalactic tidal debris from which new dwarf galaxies (TDGs – Tidal Dwarf Galaxies) are formed. In such a tidal scenario planar distribution of newly formed TDGs as well as their correlated orbital moments are a natural outcome as the TDGs are formed from a common tidal tail in a plane defined by the orbit of the interaction [2]. Interestingly, it was shown that significant amount of counter-orbiting material emerges quite naturally in tidal interactions of disk galaxies [5]. Therefore, a tidal scenario can explain even the existence of the satellites orbiting counter to the bulk of other dwarf galaxies in the planar structure.

It was argued [6] that the kinematical and morphological properties of M31 can be explained by assuming a single major merger event at the M31 location about 8.7 Gyr ago during which TDGs have been formed. Further studies revealed that the Milky Way disk of dwarf satellites, the so called Vast Polar Structure, also can be explained through the tidal tail of this ancient merger event [7]. The Vast Thin Disk of Satellites (VTDS) around M31 could have been predicted before its discovery by Ibata et al. [1] (see also [8]). Indeed, it was found post factum that the induced tidal tails by the above mentioned merger event are lying just in the VTDS plane and the positions and velocities of the VTDS dwarfs are quite accurately reproduced without any need for fine tuning the model [9]. This model also seems to provide a reasonable framework to understand some other puzzling features in the Local Group [9].

If dark matter is collisionless, then there is a problem with this simple picture, called the Zwicky Paradox in [10]: this scenario assumes that the Milky Way and Andromeda dwarf satellites are tidal dwarf galaxies. Such galaxies should be free of nonbaryonic dark matter if dark matter is collisionless [11]. Detailed observations indicate on the contrary that they are dark matter dominated [12].[1]

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[1] The Zwicky Paradox will be eliminated if the satellite galaxies are out of virial equilibrium due to tidal perturbations upon close perigalactic passages (see [13] and references therein). Such explanation of the apparent dark matter content of dwarf spheroidals might be plausible for the closest to the Milky Way dwarfs with elongated stellar structures but cannot explain the apparent dark matter content of the entire satellite population [12]. In particular, recent observations of the two distant dwarf

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The reason why TDGs are expected to be devoid of dark matter is the following [11,15]. TDGs, being recycled galaxies formed from the collisional debris, are gas dominated and their formation is dissipation supported under the crucial condition that the progenitor disks contain sufficiently massive and extended gas components [16]. Standard WIMP dark matter is assumed to be dissipationless. As a result such dark matter surrounds galaxies in the form of large nearly spherical halos supported by random motions. On the contrary, gas particles in the rotating disks of progenitor colliding galaxies have nearly circular coplanar orbits. This difference in phase space distributions indicates that galactic collisions effectively segregate dark and baryonic matter: tidal tails from which TDGs are subsequently formed should contain very little non-dissipative dark matter [15,16].

If dark matter is dissipative then the formation of a dark disk in parallel to the ordinary baryonic disk is possible in galaxies. Hidden sector dark matter, where dark matter resides in a hidden sector with its own gauge group, G', can be dissipative if G' contains an unbroken $U(1)'$ factor (sometimes called 'dark photon' in the literature). This means that the Lagrangian describing the particle physics decomposes into two sectors, one describing the standard particles and forces, and another which will contain the dark matter (we neglect possible interactions other than gravity between two sectors for a moment):

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{dark} \ . \tag{1}$$

Mirror dark matter, where the hidden sector is exactly isomorphic to the ordinary sector [17] (see also [18–20]), is an interesting special case of such a theory, for reviews see e.g. [21–25] and references there-in for a more complete bibliography. In this case there is an unbroken symmetry, which can be interpreted as space–time parity, which maps each ordinary particle, $e, \nu, u, d, \ldots, \gamma, \ldots$ onto a mass degenerate mirror partner, which we denote with a prime ($'$): $e', \nu', u', d', \ldots, \gamma', \ldots$. The symmetry ensures that the gauge self-interactions (mirror electromagnetism, etc.) have the same form and strength in the mirror sector as they do in the ordinary sector. In addition to gravity, the ordinary and mirror sector particles can interact with each other via the kinetic mixing interaction, which is both gauge invariant and renormalizable [26,27]:

$$\mathcal{L}_{mix} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} \tag{2}$$

where $F_{\mu\nu}$ ($F'_{\mu\nu}$) is the field strength tensor for the photon (mirror-photon).

In the mirror dark matter framework, spiral galaxies like M31 and the Milky Way, are currently composed of mirror particles predominately in a (roughly) spherical, pressure supported halo [28]. Additionally there may be remnant old mirror stellar objects (mirror white dwarfs, mirror neutron stars, etc.) – the spherical halo in spirals is too hot for significant mirror star formation to occur at the present epoch. The spherical halo dissipates energy due to bremsstrahlung and other processes. This energy can be replaced by the energy produced from ordinary type II supernova. This requires kinetic mixing of strength $\epsilon \sim 10^{-9}$ (to produce the energy via plasmon decay processes in the core of type II supernova [29,30]) and also that the mirror particle halo has a sufficient mirror metal component – at least around one percent by mass (so that the plasma can absorb this energy via photoionization) [28,31]. The balancing of dissipated energy with energy produced from ordinary supernovae might be enforced by the dynamics. This energy balance condition has been used in Ref. [31] to derive two scaling relations governing the (current) dark matter density profile in spiral galaxies, both of which are in agreement with observations [32]. Ref. [31] also pointed out that stringent constraints on self-interacting dark matter from elliptical galaxies and the Bullet Cluster (see also [33]), can potentially be evaded.

Although mirror dark matter seems to provide a successful picture to describe the current properties of galaxies, the role of its dissipative nature on the galaxy formation and early history is a topic that has been neglected. Naturally any discussion in this direction is speculative and certainly preliminary. With this note of caution, we now proceed to outline the emerging picture.

To understand the early growth of structure, one has to go back to early times, when density perturbations were small, i.e. $\delta\rho/\rho \ll 1$, known as the linear regime. BBN and CMB observations require asymmetric initial conditions, $T' \ll T$, $\Omega_{b'} \approx 5\Omega_b$, to hold. With $T' \ll T$, mirror-hydrogen recombination occurs very early, much earlier than ordinary hydrogen recombination. Prior to hydrogen (mirror-hydrogen) recombination, one has a ordinary (mirror) plasma strongly coupled to photons (mirror-photons). Perturbations (in Fourier space) which enter the horizon prior to recombination undergo acoustic oscillations which suppresses the growth of structure. Since mirror-hydrogen recombination occurs much earlier than hydrogen recombination this suppression is much less effective for mirror baryons. For this reason the growth of mirror baryon density perturbations are well in advance of the ordinary baryonic density perturbations by the end of the linear regime [34,35].

Eventually the perturbations reach the point where $\delta\rho/\rho \sim 1$ and gravitational collapse can occur, and linear perturbation theory is no longer valid. To gain some insight, imagine first a uniform collapsing spherical density perturbation of mass over-density ρ_0 and temperature T. For simplicity consider a collapsing plasma composed of fully ionized mirror-helium, so that $n_{e'} \approx 2n_{He'} \approx 2n_T/3$, where n_T is the total particle number density. The cooling rate per unit volume due to thermal bremsstrahlung is:[2]

$$\Gamma_{cool} = n_{e'}^2 \Lambda \tag{3}$$

where $\Lambda \sim 10^{-23}$ erg cm^3 s^{-1} for $T \sim 100$ eV. The cooling time scale, t_{cool}, is defined from $\Gamma_{cool} t_{cool} \approx n_T(3/2)T$, i.e.

$$t_{cool} \approx \frac{9T}{4\Lambda n_{e'}} \sim 100 \left(\frac{T}{100 \text{ eV}}\right)\left(\frac{10^{-2}\text{ cm}^{-3}}{n_{e'}}\right) \text{Myr}. \tag{4}$$

Another important time scale is the free fall time, t_{ff}, for the uniform collapsing spherical density perturbation. This time scale is given by:

$$t_{ff} = \sqrt{\frac{3\pi}{32 G_N \rho_0}} \tag{5}$$

where $\rho_0 = n_{He'} m_{He'} = n_{e'} m_{He'}/2$. In the absence of any heat source, perturbations satisfying $t_{cool} < t_{ff}$ can collapse unimpeded. Evaluating, t_{cool}/t_{ff}, we have:

$$\frac{t_{cool}}{t_{ff}} \sim 0.3 \left(\frac{T}{100 \text{ eV}}\right)\left(\frac{10^{-2}\text{ cm}^{-3}}{n_{e'}}\right)^{1/2}. \tag{6}$$

Evidently there is no impediment for collapse of (typical) spiral galaxy sized perturbations due to pressure effects. We thus have that in the early period (linear regime) mirror baryonic perturbations grow faster than baryonic ones given the necessary initial condition $T' \ll T$, while in the nonlinear regime, the pressure does not impede collapse of mirror baryonic structures. Therefore mirror baryons form structures first.

Within these structures the mirror baryons can collapse forming mirror stars, either in the free-fall phase or later in a dark disk. Either way rapid mirror star evolution is envisaged [37], potentially producing also mirror supernovae. With $\epsilon \sim 10^{-9}$ mirror supernovae would provide a huge flux of ordinary (X-ray?) photons. It is very natural to suppose that this radiation might have been responsible for the

satellites in the outskirts of the M31 system indicate that they are also dark matter dominated [14].

[2] The equations have been adapted from the usual treatment of baryonic physics, reviewed in e.g. [36].

re-ionization of ordinary matter at high redshift $z > 6$ inferred to exist from CMB observations. However the plasma cannot efficiently absorb radiation once the ordinary matter is ionized; the Thomson scattering cross-section is too small and photoionization is ineffective due to the low metal content at this early time. The ordinary baryons, therefore, should ultimately collapse potentially forming a separate disk. Gravitational interactions between the baryonic disk and a mirror baryonic disk (assuming both form) would cause them to merge on a fairly short time scale [38].

Eventually ordinary star formation and hence also ordinary supernovae will occur in the merged disk. With $\epsilon \sim 10^{-9}$ these ordinary supernovae would provide a huge source of mirror-photons, heating the mirror plasma component via photoionization (given the mirror metal enrichment of the plasma by this time). With sufficient heating, the mirror gas component would expand to form the spherical halo, where ultimately the energy supplied by ordinary supernova heating balances the energy dissipated due to bremsstrahlung (discussed earlier). The end result is that today, we might expect that the galactic disk would contain just the ordinary baryons and a remnant mirror stellar component, which would be surrounded by a (roughly) spherical mirror particle halo. However, the epoch of TDG formation (roughly 8.7 Gyr ago in the model of Ref. [6]) might have been early enough for the mass density of the disk to have been dominated by the mirror gas component. If this is indeed the case then TDGs can form from this dissipative material. These TDG can further accrete dark matter over time as they travel through the outer halo of their host galaxy (M31 or Milky Way). Thus, mirror dark matter, and perhaps closely related hidden sector dark matter models, might thereby explain why dwarf satellite galaxies are dark matter dominated.

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